

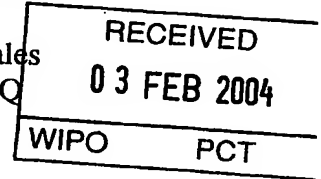


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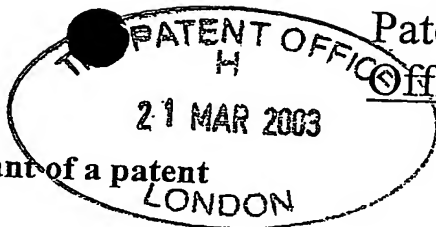
Dated 20 January 2004

# Patents Form 1/77

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24MAR03 E794355-1 D00001  
P01/7700 0.00-0306593.5

## Request for grant of a patent

LONDON

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1. Your reference MPC/9422 GB
  
2. Patent application number  
*(The Patent Office will fill in this part)* 0306593.5 21 MAR 2003
  
3. Full name, address and postcode of the  
or of each applicant *(underline all surnames)* BlazePhotonics Limited  
Finance Office, University of Bath  
The Avenue, Claverton Down  
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8141N 9001  
United Kingdom  
  
 Patents ADP number *(if you know it)*  
  
 If the applicant is a corporate body,  
give the country/state of its  
incorporation
  
4. Title of the invention Enhanced Optical Waveguide
  
5. Name of your agent *(if you have one)* Abel & Imray  
  
 "Address for service" in the United  
Kingdom to which all correspondence  
should be sent *(including the postcode)* 20 Red Lion Street  
London  
WC1R 4PQ  
  
 Patents ADP number *(if you know it)* 174001 ✓
  
6. If you are declaring priority from one  
or more earlier patent applications, give  
the country and the date of filing of the  
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Country	Priority application number <i>(if you know it)</i>	Date of filing <i>(day/month/year)</i>
  
7. If this application is divided or  
otherwise derived from an earlier UK  
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Number of earlier application	Date of filing <i>(day/month/year)</i>
  
8. Is a statement of inventorship and of  
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support of this request? *(Answer 'Yes' if:*  
*a) any applicant named in part 3 is not an*  
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11. I/We request the grant of a patent on the basis of this application.

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Abel & Imray

Abel & Imray

21 March 2003

12. Name and daytime telephone number of person to contact in the United Kingdom
- Matthew Critten (01225) 469914

Enhanced Optical Waveguide

(Ref: 0082)

The present invention is in the field of optical waveguides and relates in particular to optical waveguides that guide light by virtue of a photonic bandgap.

5 Optical fibre waveguides, which are able to guide light by virtue of a so-called photonic bandgap (PBG), were first proposed in 1995.

In, for example, "Full 2-D photonic bandgaps in silica/air structures", Birks et al., Electronics Letters, 26 October 1995, Vol. 31, No. 22, pp.1941-1942, it was proposed that a PBG may be created in an optical fibre by providing a dielectric cladding structure, which has  
10 a refractive index that varies periodically between high and low index regions, and a core defect in the cladding structure in the form of a hollow core. In the proposed cladding structure, periodicity was provided by an array of air holes that extended through a silica glass matrix material to provide a PBG structure through which certain wavelengths of light could not pass. It was proposed that light coupled into the hollow core defect would be unable to  
15 escape into the cladding due to the PBG and, thus, the light would remain localised in the core defect.

It was appreciated that light travelling through a hollow core defect, for example filled with air or even under vacuum, would suffer significantly less from undesirable effects, such as non-linearity and loss, compared with light travelling through a solid silica or doped silica  
20 fibre core. As such, it was appreciated that a PBG fibre may find application as a transmission fibre to transmit light between a transmitter and a receiver over extremely long distances, for example under the Atlantic Ocean, without undergoing signal regeneration, or as a high optical power delivery waveguide. In contrast, for standard index-guiding, single mode optical fibre, signal regeneration is typically required approximately every 80  
25 kilometres.

The first PBG fibres that were attempted by the inventors had a periodic cladding structure formed by a triangular lattice of circular air holes embedded in a solid silica matrix and surrounding a central air core defect. Such fibres were formed by stacking circular or hexagonal capillary tubes, incorporating a core defect into the cladding by omitting a single,  
30 central capillary of the stack, and then heating and drawing the stack, in a one or two step process, to form a fibre having the required structure.

International patent application PCT/DK99/00193 describes various PBG fibre structures, for example having a cladding region based on a honeycomb lattice with a central

air core. The air core is the same size as holes in the cladding region. The structure of the cladding produces a PBG and the air core, which creates a defect in the cladding, enables light to be guided in the glass in the locality of the air core.

International patent application PCT/GB00/01249 (The Secretary of State for Defence,  
 5 UK), filed on 21 March 2000, proposed the first PBG fibre to have a so-called seven-cell core defect, surrounded by a cladding comprising a triangular lattice of air holes embedded in an all-silica matrix. The core defect was formed by omitting an inner capillary and, in addition, the six capillaries surrounding the inner capillary. This fibre structure was seen to guide one or two modes in the core defect, in contrast to the previous, single-cell core defect fibre,  
 10 which appeared not to support any guided modes in the core defect.

According to PCT/GB00/01249, it appeared that the single-cell core defect fibre, by analogy to the density-of-states calculations in solid-state physics, would only support approximately 0.23 modes. That is, it was not surprising that the single-cell core defect fibre appeared to support no guided modes in its core defect. In contrast, based on the seven-fold  
 15 increase in core defect area (increasing the core defect radius by a factor of  $\sqrt{7}$ ), the seven-cell core defect fibre was predicted to support approximately 1.61 spatial modes in the core defect. This prediction was consistent with the finding that the seven-cell core defect fibre did indeed appear to support at least one guided mode in its core defect.

A preferred fibre in PCT/GB00/01249 was described as having a core defect diameter  
 20 of around  $15\mu\text{m}$  and an air-filling fraction (AFF) – that is, the proportion by volume of air in the cladding - of greater than 15% and, preferably, greater than 30%.

In “Analysis of air-guiding photonic bandgap fibres”, Optics Letters, Vol. 25, No. 2, January 15, 2000, Broeng et al. provided a theoretical analysis of PBG fibres. For a fibre with a seven-cell core defect and a cladding comprising a triangular lattice of near-circular holes,  
 25 providing an AFF of around 70%, the structure was shown to support one or two air guided modes in the core defect. This was in line with the finding in PCT/GB00/01249.

In the chapter entitled “Photonic Crystal Fibers: Effective Index and Band-Gap Guidance” from the book “Photonic Crystal and Light Localization in the 21<sup>st</sup> Century”, C.M. Soukoulis (ed.), ©2001 Kluwer Academic Publishers, the authors presented further analysis  
 30 of PBG fibres based primarily on a seven-cell core defect fibre. The optical fibre was fabricated by stacking and drawing hexagonal silica capillary tubes. The authors suggested that a core defect must be large enough to support at least one guided mode but that, as in conventional fibres, increasing the core defect size would lead to the appearance of higher

order modes. The authors also went on to suggest that there are many parameters that can have a considerable influence on the performance of bandgap fibres: choice of cladding lattice, lattice spacing, index filling fraction, choice of materials, size and shape of core defect, and structural uniformity (both in-plane and along the axis of propagation).

5 WO 02/075392 (Corning, Inc.) identifies a general relationship in PBG fibres between the number of so-called surface modes that exist at the boundary between the cladding and core defect of a PBG fibre and the ratio of the radial size of the core defect and a pitch of the cladding structure, where pitch is the centre to centre spacing of nearest neighbour holes in the triangular lattice of the exemplified cladding structure. It is suggested that when the core  
10 defect boundary, together with the photonic bandgap crystal pitch, are such that surface modes are excited or supported, a large fraction of the "light power" propagated along the fibre is essentially not located in the core defect. Accordingly, while surface states exist, the suggestion was that the distribution of light power is not effective to realise the benefits associated with the low refractive index core defect of a PBG crystal optical waveguide. The  
15 mode energy fraction in the core defect of the PBG fibre was shown to vary with increasing ratio of core defect size to pitch. In other words, it was suggested that the way to increase mode energy fraction in the core defect is by decreasing the number of surface modes, in turn, by selecting an appropriate ratio of the radial size of the core defect and a pitch of the cladding structure. In particular, WO 02/075392 states that, for a circular core structure, a  
20 ratio of core radius to pitch of around 1.07 to 1.08 provides a high mode power fraction of not less than 0.9 and is single mode. Other structures are considered, for example in Figure 7 therein, wherein the core defect covers an area equivalent to 16 cladding holes.

In a Post-deadline paper presented at ECOC 2002, "Low Loss (13dB) Air core defect Photonic Bandgap Fibre", N. Venkataraman et al. reported a PBG fibre having a seven-cell  
25 core defect that exhibited loss as low as 13dB/km at 1500nm over a fibre length of one hundred metres. The structure of this fibre closely resembles the structure considered in the book chapter referenced above. The authors attribute the relatively small loss of the fibre as being due to the high degree of structural uniformity along the length of the fibre.

PBG fibre structures are typically fabricated by first forming a pre-form and then  
30 heating and drawing an optical fibre from that pre-form in a fibre-drawing tower. It is known either to form a pre-form by stacking capillaries and fusing the capillaries into the appropriate configuration of pre-form, or to use extrusion.

For example, in PCT/GB00/01249, identified above, a seven-cell core defect pre-form structure was formed by omitting from a stack of capillaries an inner capillary and, in addition, the six capillaries surrounding the inner capillary. The capillaries around the core defect boundary in the stack were supported during formation of the pre-form by inserting  
5 truncated capillaries, which did not meet in the middle of the stack, at both ends of the capillary stack. The stack was then heated in order to fuse the capillaries together into a pre-form suitable for drawing into an optical fibre. Clearly, only the fibre drawn from the central portion of the stack, with the missing inner seven capillaries, was suitable for use as a hollow core defect fibre.

10 US patent application number US 6,444,133 (Corning, Inc.), describes a technique of forming a PBG fibre pre-form comprising a stack of hexagonal capillaries in which the inner capillary is missing, thus forming a core defect of the eventual PBG fibre structure that has flat inner surfaces. In contrast, the holes in the capillaries are round. US 6,444,133 proposes that, by etching the entire pre-form, the flat surfaces of the core defect dissolve away more  
15 quickly than the curved surfaces of the outer capillaries. The effect of etching is that the edges of the capillaries that are next to the voids fully dissolve, while the remaining capillaries simply experience an increase in hole-diameter. Overall, the resulting pre-form has a greater fraction of air in the cladding structure and a core defect that is closer to a seven-cell core defect than a single cell core defect.

20 PCT patent application number WO 02/084347 (Corning, Inc.) describes a method of making a pre-form comprising a stack of hexagonal capillaries of which the inner capillaries are preferentially etched by exposure to an etching agent. Each capillary has a hexagonal outer boundary and a circular inner boundary. The result of the etching step is that the centres of the edges of the hexagonal capillaries around the central region dissolve more quickly than  
25 the corners, thereby causing formation of a core defect. In some examples, the circular holes are offset in the inner hexagonal capillaries of the stack so that each capillary has a wall that is thinner than its opposite wall. These capillaries are arranged in the stack so that their thinner walls point towards the centre of the structure. An etching step, in effect, preferentially etches the thinner walls first, thereby forming a seven-cell core defect.

30 In arriving at the present invention, the inventors have appreciated and demonstrated that, while the size of a core defect is significant in determining certain characteristics of a PBG waveguide, the form of a boundary at the interface between core and cladding also plays a significant role in determining certain characteristics of the waveguide. By way of example,

as will be described in detail hereafter, the inventors have shown that, for given PBG core and cladding structures, variations in only the thickness of the boundary, at the interface between the core and cladding, can cause significant changes in the characteristics of a respective waveguide.

5 According to a first aspect, the present invention provides an optical waveguide, comprising:

a core, comprising an elongate region of relatively low refractive index;

a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light including an operating wavelength of light, the structure, in a transverse  
10 cross section of the waveguide, surrounding the core and comprising elongate relatively low refractive index regions interspersed with elongate relatively high refractive index regions; and

a relatively high refractive index boundary at the interface between the core defect and the photonic bandgap structure, the boundary having a thickness around the core such that the  
15 boundary is an anti-resonant reflector at the operating wavelength of light.

It has been widely reported that light may be guided in a PBG fibre by virtue of a cladding which provides a PBG. It has also been reported by Litchinitser *et al.*, Opt Lett., Vol. 27 (2002) pp. 1592-1594, that light may be guided in a PBG-like fibre predominantly by anti-resonant reflection in multiple cladding layers. Litchinitser *et al.* describe a fibre structure  
20 comprising a low index core surrounded by plural concentric layers of high and low index material, the relative thicknesses of which were chosen to provide an anti-resonant cladding structure for confining light to the core region. Litchinitser *et al.* also mention a fibre structure consisting of a silica core surrounded by holes filled with high index liquid. In that case the silica represents the low index medium and the filled holes are the features that act as  
25 resonators. It was suggested that, at their anti-resonant wavelengths, the filled holes could substantially exclude light and thus confine light to the relatively low-index silica core. It was also stated that numerical simulations on such a structure were very time consuming and so the study was limited to the concentric ring structure.

The present inventors have shown that confinement of light to a core of a PBG fibre,  
30 which confines light to the core region by virtue of a photonic bandgap, may be enhanced by providing, at the interface between the core and the photonic bandgap cladding, a boundary which is tuned to be substantially anti-resonant.



Considering, for example, an air-core PBG fibre, the inventors have determined that the geometry of the region of the boundary between the air core and the photonic bandgap cladding structure has profound effects on the modal properties of the fibre. In particular, the inventors have appreciated that the number of guiding modes within the band gap, the fraction  
 5 of the light power of the guided modes confined within the air core and the field intensity of these modes at the air-silica interfaces all vary sensitively with the geometry within the region. In particular, the inventors have shown that by tailoring the geometry, the properties of an LP<sub>01</sub>-like mode (when present), which possesses an approximately Gaussian intensity profile towards the centre of the core, can be tailored so that over 99% of the light is confined  
 10 within air, and predominantly in the core. This implies that loss due to Rayleigh scattering in the silica may be suppressed by up to two orders of magnitude and that nonlinearity may be substantially reduced compared with standard index guiding single mode fibre. Also, the inventors have demonstrated that the core boundary geometry can be designed to reduce the field intensity of this mode strongly in the vicinity of the air-silica interfaces. This has the  
 15 effect of reducing both the small scale interface roughness scattering, which is discussed in detail hereafter, and the mode coupling due to longer range fibre variations..

The inventors have determined that the design of a core-cladding interface, or boundary region, can exploit an anti-resonance effect to strongly enhance the power in air fraction,  $\eta$ , and reduce the field intensity at the air-silica interfaces of the LP<sub>01</sub>-like mode. In  
 20 particular, the inventors have found that the geometry giving rise to the anti-resonance can be based either on a continuous silica boundary layer encircling the air core, such as in the example shown in Figure 1, or on a number of localised regions of silica existing around the core boundary, such as in the example shown in Figure 2.

The inventors suggest that the mechanism by which an anti-resonance of a continuous  
 25 core surround can occur may be understood by considering a circular tube of silica of constant thickness  $t$  and mean radius  $R$ , of the inner and outer silica/air interfaces, surrounded by air, as shown in Figure 3. The properties of this system can be analysed exactly by expressing the fields in regions I, II and III in terms of Bessel functions using known techniques. The cylindrical symmetry implies that modes decouple according to an integer  $m$ , which governs  
 30 the azimuthal variation of the fields around the tube. An eigenvalue equation for each  $m$  may be generated by applying electromagnetic boundary conditions at the dielectric interfaces and the guiding and leaky modes of the structure may be readily obtained from the solutions to the eigenvalue equations. The guided modes, which are concentrated in the silica, satisfy

$\text{Re}[\beta] > \omega/c, \text{Im}[\beta] = 0$ . The leaky modes require analytic continuation to complex  $\beta$  values; only solutions which possess small imaginary  $\beta$  components are retained. At low values of  $m$ ,  $\text{Re}[\beta] \approx \omega/c$  for the leaky mode solutions lies close to and just below the air light-line value  $\text{Re}[\beta] < \omega/c$ . At high values of  $m$ , low loss leaky "whispering gallery" modes can exist  
 5 further from the light line in rings of sufficiently large radius and thickness.

The leaky air modes can be labelled in an analogous way to the guided modes of standard index guiding optical fibres. Of particular interest is the  $\text{LP}_{01}$ -like leaky mode, which is the analogue of the fundamental mode of a standard telecommunications fibre. The  $\text{LP}_{01}$ -like mode is found to have a concentration of light power within the hole in the tube and  
 10 has an approximately Gaussian field intensity profile close to the centre of the hole. The  $\beta$ -value of this mode lies close to the air light line, so that the air-silica interfaces act as strong reflectors of the light. This gives rise to strong confinement, as evidenced by the small value of  $\text{Im}[\beta]$  associated with the mode. The  $\text{LP}_{01}$ -like leaky mode confinement, for a given tube radius  $R$ , is found to be strongly dependent upon the thickness  $t$ .

15 Figure 4 shows the dependence of  $\text{Im}[\beta]$  on thickness  $t$ , for a mean tube radius of  $6\mu\text{m}$  and a wavelength  $\lambda = 1.55\mu\text{m}$ . The broad minimum occurring around  $t = 0.4\mu\text{m}$  is believed to be due to an anti-resonance phenomenon. Destructive interference occurs for (Hankel) waves which are multiply reflected at the dielectric interfaces. The round-trip phase accumulated by a wave that emanates from the inner interface, propagates outwards to the  
 20 outer interface, reflects and propagates inwards to the inner interface and is again reflected, is close to  $\pi$ . More generally, anti-resonances occur around thickness values giving rise to a round-trip phase given by  $(2n+1)\pi$ , where  $n$  is an integer satisfying  $n \geq 0$ . For tube radii satisfying  $R \gg \lambda$  (where  $\lambda$  is the operating wavelength), thickness  $t$  which gives rise to anti-resonance is determined from

25

$$t = \frac{\lambda}{4\sqrt{n_{\text{sil}}^2 - 1}}(2n + 1), \quad (1)$$

where  $n_{\text{sil}}$  is the refractive index of silica. As can be seen  $t$  is independent of the radius  $R$ . In this regime, the boundaries are acting as locally planar interfaces. More generally still, anti-  
 30 resonances lie between resonances, which in this case occur at

$$t \approx \frac{\lambda}{4\sqrt{n_{sil}^2 - 1}} 2n, \quad n \geq 1. \quad (2)$$

At resonances, the field is concentrated within the silica of the tube.

Figure 5 shows the mode field intensity  $I$  of the  $LP_{01}$ -like leaky mode for a tube with mean radius  $R=6\mu\text{m}$ , thickness  $t=0.392\mu\text{m}$  and wavelength  $1.55\mu\text{m}$ , which corresponds to anti-resonance. Of course, to benefit from anti-resonance, it is not necessary to operate at exact anti-resonance. Indeed, there is a broad range between resonance peaks where a waveguide benefits from a boundary tuned to have some degree of anti-resonance. It can be seen that a near null appears very close to the inner dielectric interface and that the intensity at the outer interface is 22dB lower than the intensity at the centre of the hole. This field suppression at the interfaces is a feature of anti-resonance. Exploitation of the anti-resonance phenomenon both maximises the confinement of the  $LP_{01}$ -like leaky mode and largely minimises the field at the boundaries and hence the interface roughness scattering (discussed below). Of course, any well-confined, leaky mode in the core, for example a  $TE_{01}$ -like mode, would benefit in the same way as the  $LP_{01}$ -like mode.

Figure 6 shows plots of the mode spectra of an anti-resonant tube of radius  $R=6\mu\text{m}$  and  $t=0.392$ , including all guided modes and leaky modes within  $\Delta\beta = 0.15\mu\text{m}^{-1}$  of the air light line at  $\lambda=1.55\mu\text{m}$ , and compares it with the spectrum for a thinner silica ring of thickness  $t=0.1\mu\text{m}$ , which is the approximate thickness of a cladding structure vein according to a preferred structure, as described hereinafter. This range of  $\beta$  is chosen to correspond to the band-gap width of a typical PBG fibre cladding. It is seen that within this region, the thicker anti-resonant tube actually possesses a smaller number of modes than the thinner one. The interface field intensity reduction and the mode number reduction implies that mode coupling effects, due to fluctuations on a length scale exceeding about  $20\mu\text{m}$ , can be expected to be lower for a thicker anti-resonant boundary than a thinner one.

The inventors have applied the foregoing principles to a numerical investigation of continuous core surrounds, or boundaries, having shapes that are more easily fabricated in practice, for example a dodecagonal boundary as shown in Figure 7. The results are compared herein with the circular geometry.

At least initially, the boundary may be considered in the absence of any cladding material; it is taken to be bounded by air. The dodecagonal boundary, which is a natural core

surround shape in PBG fibre manufactured using stacked silica tubes, as will be described hereinafter, is found to possess a  $LP_{01}$ -like leaky mode which shows an anti-resonance effect almost identical with that of a circular tube of the same mean radius. The confinement ability of this mode is found to be only very slightly compromised by the sharp corners associated with this geometry. A near null of the field intensity again occurs very close to the inner dielectric interface. The thickness at anti-resonance of this shape is very close to that of the circular tube. The number of guided and leaky modes of this shape at anti-resonance is found to be similar to that of the tube over the PBG region, although modes possessing faster azimuthal variation (high effective  $m$ ) are shifted significantly by the change in geometry and the confinement of leaky modes with high effective  $m$  is reduced by the appearance of corners.

The inventors have considered a full PBG fibre geometry, as shown in Figure 8, with band gap cladding material surrounding a continuous core boundary. It is found that the anti-resonance phenomenon associated with the continuous core surround occurs for these structures also. This is evidenced by scanning over boundary thickness  $t$  and numerically calculating the  $LP_{01}$ -like mode solutions.

As a function of  $t$ , broad maxima in the fraction  $\eta$  of the light power in air are observed, together with broad minima in F-factor (described below), which measures field intensity at the dielectric interfaces and gives a direct relative measure of the strength of small scale interface roughness scattering and provides an indication of the relative strength of mode coupling effects due to longer scale fluctuations.

In fact, the thickness for anti-resonance for the core surround bounded by air can be used as an indication of the boundary thickness required for anti-resonance in the PBG fibre geometry, as will be demonstrated. The thickness  $t$  at anti-resonance for the latter geometry is found to be a little lower than for the former one. This difference is believed to be a function of the silica associated with the PBG cladding structure, which connects onto the outer surface of the boundary. In other words, the boundary has an 'effective thickness', which is greater than the actual thickness, where effective thickness will vary depending on the form of the cladding which meets the outer surface of the boundary. Furthermore, examination of the mode field intensity of the  $LP_{01}$ -like mode shows that near nulls appear close to the inner surface of the boundary in the PBG fibre at maximum  $\eta$  and minimum F-factor, just as they do for the core surround in air at anti-resonance. This confirms the anti-resonance mechanism

for PBG fibre geometry. Hence, F-factor,  $\eta$  and anti-resonance are proxies for one another in that determining any one provides specific information about the other two.

According to a second aspect, the present invention provides an optical waveguide, comprising:

- 5 a core, comprising an elongate region of relatively low refractive index;
- a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light, the structure, in a transverse cross section of the waveguide, surrounding the core and comprising elongate relatively low refractive index regions interspersed with elongate relatively high refractive index regions; and
- 10 a relatively high refractive index boundary at the interface between the core defect and the photonic bandgap structure, the boundary having a thickness around the core such that, in use, light guided by the waveguide is guided in a transverse mode in which, in the transverse cross-section, more than 95% of the guided light is in the regions of relatively low refractive index in the waveguide.
- 15 As indicated, guiding light in a region of relatively low refractive index has the advantage that losses, nonlinear effects and other material effects are generally lower in such regions, particularly if the region is a region of air or a gas. Thus, preferably in the transverse cross-section, ever more of the light may be guided in the regions of relatively low refractive index in the PBG structure and the core: preferably more than 96%, 97%, 98%, 99%, 99.3%,
- 20 99.5% or even 99.9% of the light is in those regions.

The boundary may have a thickness such that, in use, light guided by the waveguide is guided in a transverse mode in which, in the transverse cross-section, more than 50% of the guided light is in the region of relatively low refractive index in the core. It is significant that the inventors have recognised that the light need not be in the core region for beneficial

25 effects to be achieved. Thus, the boundary may have a shape such that, in use, light guided by the waveguide is guided in a transverse mode in which, in the transverse cross-section, more than 1% of the guided light is in the regions of relatively low refractive index in the photonic bandgap structure. It may be that still more of the guided light is in those regions in the PBG structure: more than 2%, more than 5% or even more than 10% of the light may be in those

30 regions.

The boundary may have a thickness such that, in use, light guided by the waveguide is guided in a transverse mode providing an F-factor of less than  $0.23\mu\text{m}^{-1}$  (at  $1.55\mu\text{m}$ , or less than  $0.7\Lambda^{-1}$  for structures having a periodic cladding with a pitch  $\Lambda$ ).

F-factor has been identified by the present inventors as a useful figure of merit which relates to how the guided light propagating in a PBG fibre is subject to scattering from small scale irregularities of the air-silica interfaces. F-factor is also believed to be a strong indicator of likely mode-coupling characteristics of a PBG-fibre.

5 Scattering due to small scale irregularities acts in addition to the Rayleigh scattering due to index inhomogeneity within silica, or any other such optical guiding medium. The latter loss mechanism is strongly suppressed in air-core PBG fibres, if most of the light power  $\eta$  is in air. It remains to ascertain the limit that hole interface scattering places on loss, given that some interface roughness is always present. The amount of scattering associated with air-  
10 silica boundaries can be minimised by ensuring that impurities are eliminated during the draw process; such impurities can act as scattering (and absorption) centres directly, and can operate as nucleation sites for crystallite formation. With these imperfections removed, there still remains interface roughness governed by the thermodynamics of the drawing process. The inventors believe that such fluctuations are likely to be difficult or impossible to remove  
15 altogether.

The Rayleigh scattering due to small scale roughness at the air-silica interfaces may be calculated by applying a perturbation calculation. The analysis has a simple interpretation in terms of effective particulate scatterers distributed on the interfaces. If the root-mean square (RMS) height roughness is  $h_{\text{rms}}$  and the correlation lengths of the roughness along the hole  
20 direction and around the hole perimeter are  $L_z$  and  $L_\phi$  respectively, then a typical scatterer has a volume  $h_{\text{rms}}L_zL_\phi$ . The induced dipole moment of the typical scatterer is then given by

$$\mathbf{p} = \Delta\epsilon \mathbf{E}_0 h_{\text{rms}} L_z L_\phi \quad (3)$$

25 where  $\Delta\epsilon$  is the difference in dielectric constant between silica and air, and  $\mathbf{E}_0$  is the E-field strength at the scatterer. This induced dipole moment radiates a power, in the free space approximation, given by

$$P_{\text{sc}} = \frac{1}{12\pi} \left( \frac{\omega}{c} \right)^4 \left( \frac{\epsilon_0}{\mu_0} \right)^{1/2} |\mathbf{p}|^2 = \frac{1}{12\pi} \left( \frac{\omega}{c} \right)^4 \Delta\epsilon^2 h_{\text{rms}}^2 L_z^2 L_\phi^2 \left( \frac{\epsilon_0}{\mu_0} \right)^{1/2} |\mathbf{E}_0|^2. \quad (4)$$

The number density of particles on the interface will be  $\sim 1/(L_z L_\phi)$  so that the total radiated power from a section of length  $L$  of the perturbed fibre will be approximately

$$P_{\text{rad}} \sim \frac{1}{12\pi} \left( \frac{\omega}{c} \right)^4 \Delta \varepsilon^2 h_{\text{rms}}^2 L_z L_\phi L \left( \frac{\varepsilon_0}{\mu_0} \right)^{1/2} \oint_{\text{perimeters}}^{\text{hole}} ds |\mathbf{E}_0|^2 \quad (5)$$

5

The loss rate is thus given by

$$\gamma = \frac{P_{\text{rad}}}{P_0 L} \sim \frac{1}{6\pi} \left( \frac{\omega}{c} \right)^4 \Delta \varepsilon^2 h_{\text{rms}}^2 L_z L_\phi \left( \frac{\varepsilon_0}{\mu_0} \right)^{1/2} \frac{\oint_{\text{perimeters}}^{\text{hole}} ds |\mathbf{E}_0|^2}{\int dS (\mathbf{E}_0 \wedge \mathbf{H}_0^*) \cdot \hat{\mathbf{z}}} \quad (6)$$

10 where the incident power  $P_0$  has been expressed as a Poynting flux.

Equation (6) shows that the mode shape dependence of the Rayleigh interface roughness scattering strength is governed by an F-factor, given by

$$F = \left( \frac{\varepsilon_0}{\mu_0} \right)^{1/2} \frac{\oint_{\text{perimeters}}^{\text{hole}} ds |\mathbf{E}_0(\mathbf{r}')|^2}{\int_{\text{x-section}} dS (\mathbf{E}_0 \wedge \mathbf{H}_0^*) \cdot \hat{\mathbf{z}}} \quad (7)$$

15

The inventors have found that a comparison of the interface scattering strength from guided modes of different fibres with similar interface roughness properties can be based purely on the F-factor. Indeed, the thermodynamic limit to surface roughness is not expected to vary significantly with the details of the fibre geometry, so that the F-factor can be used  
20 directly as a figure of merit for any fibre which has interfaces which cause scattering and contribute to loss.

According to a third aspect, the present invention provides an optical waveguide, comprising:

a core, comprising an elongate region of relatively low refractive index;

25 a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light, the structure, in a transverse cross section of the waveguide, surrounding the core and comprising elongate relatively low refractive index regions interspersed with elongate relatively high refractive index regions; and

a relatively high refractive index boundary at the interface between the core defect and the photonic bandgap structure, the boundary having a thickness around the core such that, in use, light guided by the waveguide is guided in a transverse mode providing an F-factor of less than  $0.23\mu\text{m}^{-1}$  (at  $1.55\mu\text{m}$ , or less than  $0.7\Lambda^{-1}$  for structures having a periodic cladding  
5 with a pitch  $\Lambda$ ).

Preferably, still lower F-factors are provided: less than  $0.17\mu\text{m}^{-1}$ , less than  $0.1\mu\text{m}^{-1}$ , less than  $0.07\mu\text{m}^{-1}$ , less than  $0.06\mu\text{m}^{-1}$ , less than  $0.05\mu\text{m}^{-1}$ , less than  $0.33\mu\text{m}^{-1}$  or even less than  $0.02\mu\text{m}^{-1}$  are preferred (for an operating wavelength of  $1.55\mu\text{m}$ ) - for a PBG fibre that has a periodic photonic bandgap structure, with a pitch  $\Lambda$ , these values scale with pitch and  
10 become less than  $0.5\Lambda^{-1}$ , less than  $0.3\Lambda^{-1}$ , less than  $0.2\Lambda^{-1}$ , less than  $0.17\Lambda^{-1}$ , less than  $0.15\Lambda^{-1}$ , less than  $0.10\Lambda^{-1}$  or even less than  $0.05\Lambda^{-1}$  respectively.

A more rigorous calculation of small scale interface roughness can be derived which takes into account the details of the surface roughness spectrum and deviations from the free space approximation. The latter effect is embodied by a local density of states (LDOS)  
15 correction factor appearing in the integrand of the numerator integral in equation (7). Ideally, to minimise the interface loss, the field intensity of the guiding mode multiplied by the LDOS factor should be maintained as small possible at the interfaces. In practise, the LDOS correction is found to be small even for (silica/air) PBG fibres in comparison with the guided mode field intensity factor; so that the F-factor given in equation (7) may be used to compare  
20 the interface scattering strength from guided modes of different fibre designs.

The effect of the scattering from crystallites which have formed close to the air/silica interfaces can be calculated in a similar way to the geometrical roughness considered above. Assuming the number density per unit interface length and the size of the crystallites is independent of fibre design, again F-factor can be used directly to compare the interface  
25 scattering strengths.

The features next discussed may be found in embodiments of any one of the preceding three aspects of the invention (relating to anti-resonance, proportion  $\eta$  of light in the relatively low refractive index regions or F-factor).

The boundary may have a substantially constant thickness around the core.  
30 Alternatively, the boundary may have a thickness that varies around the core. In either case, thickness variations at points where the cladding joins the boundary may be ignored.

The thickness may equal  $x\lambda$  around at least a proportion  $y$  of the boundary, where  $\lambda$  is the selected operating wavelength,  $x > 0.16$  and  $y > 0.5$ . Alternatively,  $x$  may be greater than



0.18, 0.19, or 0.20. In addition, or alternatively,  $y$  may be greater than 0.6, 0.8 or be substantially equal to 1.0.

In the transverse cross section, the photonic bandgap structure may comprise an array of the relatively low refractive index regions separated from one another by the relatively high refractive index regions. The array may be substantially periodic. Of course, the array need not be periodic, as described in the paper by N. M. Litchinitser et al. discussed above.

It is highly unlikely in practice that a photonic bandgap structure according to the present invention will comprise a 'perfectly' periodic array, due to imperfections being systematically or accidentally introduced into the structure during its manufacture and/or perturbations being introduced into the array by virtue of the presence of the core defect. The present invention is intended to encompass both perfect and (purposely or accidentally) imperfect structures. Likewise, any reference to "periodic", "lattice", or the like herein, imports the likelihood of imperfection.

The array may be a substantially triangular array. Other arrays, of course, may be used, for example, square, hexagonal or Kagomé, to name just three.

The array may have a characteristic primitive unit cell and a pitch  $\Lambda$ . The pitch may be between three and six microns.

The boundary may have a thickness  $t$ , wherein,  $t = u\Lambda$  for a proportion of the boundary  $y$ , where  $u > 0.08$  and  $y > 0.5$ .  $u$  may be even greater, for example  $u > 0.09$ , 0.1 or 0.11. Additionally, or alternatively,  $y$  may be greater, for example  $y > 0.6$ , 0.8 or may be equal to 1.0.

The boundary region may comprise, in the transverse cross-section, a plurality of relatively high refractive index boundary veins joined end-to-end around the boundary between boundary nodes, each boundary vein being joined between a leading boundary node and a following boundary node, and each boundary node being joined between two boundary veins and to a relatively high refractive index region of the photonic bandgap structure.

At least two of the higher index regions in the photonic bandgap structure may be connected to each other. Indeed, the higher index regions in the photonic bandgap structure may be interconnected.

The photonic bandgap structure may comprise an arrangement of isolated relatively low refractive index regions separated by connected regions of relatively high refractive index.

The core may have, in the transverse cross-section, an area that is significantly greater than the area of at least some of the relatively low refractive index regions of the photonic bandgap structure. The core may have, in the transverse cross-section, an area that is greater than twice the area of at least some of the relatively low refractive index regions of the  
5 photonic bandgap structure.

The core may have, in the transverse cross-section, an area that is greater than the area of each of the relatively low refractive index regions of the photonic bandgap structure.

The core may have, in the transverse cross-section, a transverse dimension that is greater than the pitch  $\Lambda$ .

10 The core may correspond to the omission of a plurality of unit cells of the photonic band-gap structure, for example, the core may correspond to the omission of three, four, six, seven, ten or nineteen unit cells of the photonic band-gap structure. The core may correspond to the omission of more than nineteen unit cells of the photonic band-gap structure.

At least some of the relatively low refractive index regions may be voids filled with air  
15 or under vacuum.

At least some of the relatively low refractive index regions may be voids filled with a liquid or a gas other than air. The region of relatively low refractive index that makes up the core may comprise the same or a different material compared with the regions of relatively low refractive index in the photonic bandgap structure.

20 In some embodiments, at least some of the relatively high refractive index regions comprise silica glass. The glass may be un-doped or doped with index raising or lowering dopants. Alternatively, the relatively high refractive index may comprise another solid material, for example a different kind of glass or a polymer.

The relatively low refractive index regions may make up more than 75% by volume of  
25 the photonic bandgap structure. The relatively low refractive index regions may make around 87.5% by volume of the photonic bandgap structure.

The waveguide may support a mode having a mode profile that closely resembles the fundamental mode of a standard optical fibre. An advantage of this is that the mode may readily couple into standard, single mode optical fibre.

30 Alternatively, or in addition, the waveguide may support a non-degenerate mode. This mode may resemble a  $TE_{01}$  mode in standard optical fibres.

Preferably, in either case, said mode supports a maximum amount of the mode power in relatively low refractive index regions compared with other modes that are supported by the waveguide.

At least some of the boundary veins may be substantially straight. In some  
5 embodiments, substantially all of the boundary veins are substantially straight. Alternatively, or additionally, at least some of the boundary veins may be bowed outwardly from the core defect.

According to a fourth aspect, the present invention provides an optical fibre comprising a waveguide according to any of the first three aspects of the present invention.

10 According to a fifth aspect, the present invention provides an optical fibre transmission system comprising a transmitter, a receiver and an optical fibre, according to the fourth aspect of the present invention, for transmitting light between the transmitter and the receiver.

According to a sixth aspect, the present invention provides data conditioned by having  
15 been transmitted through a waveguide or transmission system, as described above. As in any transmission system, data that is carried by the system acquires a characteristic 'signature' determined by a transfer function of the system. By characterising the system transfer function sufficiently accurately, using known techniques, it is possible to match a model of the input data, operated on by the transfer function, with real data that is output (or received) from  
20 the transmission system.

Also according to the invention there is provided a method of forming elongate waveguide, comprising the steps:

forming a preform stack by stacking a plurality of elongate elements;

25 omitting, or substantially removing at least one elongate element from an inner region of the stack; and

heating and drawing the stack, in one or more steps, into a waveguide of a type described above as being according to the invention.

Also according to the invention there is provided a method of forming elongate waveguide for guiding light, comprising the steps:

30 simulating the waveguide in a computer model, the waveguide comprising a core, comprising an elongate region of relatively low refractive index and a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light, the structure comprising elongate regions of relatively low refractive index interspersed with

elongate regions of relatively high refractive index, including a boundary region of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core, wherein properties of the boundary region are represented in the computer model by parameters; and

- 5 finding a set of values of the parameters that, according to the model, increases or maximises how much of the light guided by the waveguide is in the regions of relatively low refractive index in the waveguide.

Also according to the invention, there is provided a method of forming elongate waveguide for guiding light, comprising the steps:

- 10 simulating the waveguide in a computer model, the waveguide comprising a core, comprising an elongate region of relatively low refractive index and a photonic bandgap structure arranged to provide a photonic bandgap over a range of frequencies of light, the structure comprising elongate regions of relatively low refractive index interspersed with elongate regions of relatively high refractive index, including a boundary region of relatively high refractive index that surrounds, in a transverse cross-section of the waveguide, the core wherein properties of the boundary region are represented in the computer model by parameters;

finding a set of values of the parameters that, according to the model, decreases or minimises the F-factor of the waveguide.

- 20 Other aspects and embodiments of the present invention will become apparent from reading the following description and claims and considering the following drawings.

Embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings, of which:

- Figure 1 is a diagram of a transverse cross section of a PBG fibre structure having a generally constant thickness core boundary;

Figure 2 is a diagram of a transverse cross section of a PBG fibre structure having a varying thickness core boundary;

Figure 3 is a diagram which illustrates a transverse cross section of a circular tube of silica in air;

- 30 Figure 4 is a graph which plots the imaginary part of the longitudinal propagation constant  $\beta$  as a function of tube thickness  $t$ ;

Figure 5 is a graph which plots the radial dependence of the  $LP_{01}$ -like leaky mode field intensity, for an anti-resonant silica tube of the kind shown in Figure 1;

Figure 6 are the mode spectra of silica tubes of radius  $R$  at thicknesses  $t=0.392\text{mm}$  and  $t=0.1\text{mm}$ ;

Figure 7 is a diagram which illustrates the geometry of a dodecagonal core surround;

Figure 8 is a diagram of a transverse cross section of a PBG fibre structure of the kind  
5 used in embodiments of the present invention;

Figures 9a and 9b are graphs which plot light power in air and F-factor respectively for PBG fibre structures having different boundary thicknesses;

Figure 10 is a diagram illustrating an arrangement of capillaries and rods for use in forming a waveguide structure according to an embodiment of the present invention;

10 Figure 11 is a scanning electron micrograph of a structure made from a pre-form according to Figure 10;

Figure 12 is a diagram of an alternative embodiment of the present invention; and

Figure 13 is a diagram of another alternative embodiment of the present invention.

Figure 8 is a representation of a transverse cross-section of a PBG fibre waveguide  
15 structure of the kind used in embodiments of the present invention. In the Figure, the black regions represent fused silica glass and the white regions represent air holes in the glass. As illustrated, the cladding 100 comprises a triangular array of generally hexagonal cells 105, surrounding a seven-cell core defect 110. A core defect boundary 145 is at the interface between the cladding and the core defect. The core defect boundary has twelve sides -  
20 alternating between six relatively longer sides 140 and six relatively shorter sides 130 - and is formed by omitting or removing seven central cells; an inner cell and the six cells that surround the inner cell. The cells would have typically been removed or omitted from a pre-form prior to drawing the pre-form into the fibre. As the skilled person will appreciate, although a cell comprises a void, or a hole, for example filled with air or under vacuum, the  
25 voids or holes may alternatively be filled with a gas or a liquid or may instead comprise a solid material that has a different refractive index than the material that surrounds the hole. Equally, the silica glass may be doped or replaced by a different glass or other suitable material such as a polymer.

The waveguide of Figure 8 has a substantially periodic structure. However, as  
30 discussed above, N. M. Litchinitser et al. have demonstrated that photonic bandgaps may be achieved in non-periodic structures. The properties of the core-cladding boundary are also important in non-periodic PBG structures and the invention is not limited to substantially

periodic structures but encompasses structures with some or even a high degree of aperiodicity or irregularity in the cladding structure.

Hereafter, and with reference to Figure 8, a region of glass 115 between any two holes is referred to as a "vein" and a region of glass 120 where veins meet is referred to as a  
5 "node".

The core defect boundary 145 comprises the inwardly-facing veins of the innermost ring of cells that surround the core defect 110.

In practice, for triangular lattice structures that have a large air-filling fraction, for example above 75%, most of the cladding holes 105 assume a generally hexagonal form, as  
10 shown in Figure 8, and the veins are generally straight.

The cells forming the innermost ring around the boundary of the core defect, which are referred to herein as "boundary cells", have one of two general shapes. A first kind of boundary cell 125 is generally hexagonal and has an innermost vein 130 that forms a relatively shorter side of the core defect boundary 145. A second kind of boundary cell 135  
15 has a generally pentagonal form and has an innermost vein 140 that forms a relatively longer side of the core defect boundary 145.

Referring again to Figure 8, there are twelve boundary cells 125, 135 and twelve nodes 150, which are referred to herein as "boundary nodes", around the core defect boundary 145. Specifically, as defined herein, there is a boundary node 150 wherever a vein  
20 between two neighbouring boundary cells meets the core defect boundary 145. In Figure 8, these boundary nodes 150 have slightly smaller diameters than the cladding nodes 160. For the present purposes, the veins 130 & 140 that make up the core defect boundary are known as "boundary veins".

The structure in Figure 8 and each of the following examples of different structures  
25 closely resemble practical optical fibre structures, which have either been made or may be made according to known processes or the processes described hereinafter. The structures share the following common characteristics:

a pitch  $\Lambda$  of the cladding chosen between values of approximately  $3\mu\text{m}$  and  $6\mu\text{m}$  (this value may be chosen to position core-guided modes at an appropriate wavelength for a  
30 particular application);

a thickness  $t$  of the cladding veins of 0.0548 times the chosen pitch  $\Lambda$  of the cladding structure (or simply  $0.0548\Lambda$ );

an air-filling fraction  $\eta$  in the cladding of approximately 87.5%.

As described above, the present inventors have determined that it is possible to control the performance of PBG fibres in particular by minimising the F-factor or maximising the amount of light that propagates in air within the fibre structure, even if some light is not in the core, in order to benefit from the properties of PBG fibres, such as reduced absorption, non-linearity and, in addition, reduced mode coupling. As has been described, light in air and F-factor are proxies to anti-resonance exhibited by the core boundary.

To this end, the inventors have analysed a significant number of PBG fibres in which only the thickness of the boundary veins has been varied, from 1.4 times the thickness of the cladding veins to 2.4 times the thickness of the cladding veins, in steps of 0.1 times the thickness of the cladding veins. Specific details of the structures are provided in Table 1 below.

Boundary vein thickness relative to:					
Cladding vein thickness (%)	Cladding pitch $\Lambda$	Operating wavelength $\lambda$ (%)	Absolute thickness ( $\mu\text{m}$ )	Light power in air $\eta$ (%)	F-factor ( $\Lambda^{-1}$ )
140	0.077	16.0	0.248	92	1.68
150	0.082	17.1	0.266	97	0.67
160	0.088	18.3	0.283	98	0.38
170	0.093	19.4	0.301	98	0.34
180	0.099	20.5	0.318	99	0.23
190	0.104	21.7	0.336	99	0.23
200	0.110	22.8	0.354	98	0.29
210	0.115	24.0	0.371	97	0.46
220	0.121	25.1	0.389	90	1.17
230	0.126	26.3	0.407	89	1.06
240	0.132	27.4	0.425	95	0.57

Table 1.

In Table 1, boundary vein thickness is presented in four alternate ways. The first column shows boundary vein thickness relative to cladding vein thickness. The second column shows boundary vein thickness relative to the selected pitch  $\Lambda$  of the cladding

structure. The third column shows boundary vein thickness as a function of the selected operating wavelength  $\lambda$ . These three measures are scalable and remain the same for a broad range of PBG fibre structure pitches and operating wavelengths for structures within the same bandgap. The fourth column shows absolute boundary vein thickness in  $\mu\text{m}$  for an operating  
 5 wavelength of  $1.55\mu\text{m}$  and is, thus, not scalable.

The fifth and sixth columns show values for percentage of light power in air  $\eta$  and F-factor respectively for the eleven structures. F-factor is shown in terms of  $\Lambda^{-1}$  and is thus relevant to PBG fibres with periodic cladding structures, and so remains constant as pitch or wavelength varies. It is easy to calculate absolute F-factor in terms of  $\mu\text{m}^{-1}$  for an absolute  
 10 wavelength of  $1.55\mu\text{m}$  by dividing the F-values by 3 (since pitch is selected to be about  $3\mu\text{m}$  for a  $1.55\mu\text{m}$  operating wavelength).

The light-in-air and F-factor of a particular structure is directly measurable. The method of measuring light-in-air involves taking a near-field image of light as it leaves the structure, overlaying it on a scanning electron micrograph (SEM) or atomic force microscopy  
 15 (AFM) image of the structure and directly calculating the % light-in-air from the overlap of the two images, although care needs to be taken since the field can vary rapidly across the boundary between air and glass. Such techniques will be readily apparent to those skilled in the art of optical fibre measurement techniques.

The light-in-air and F-factor can also be calculated more indirectly for a real fibre  
 20 structure by the following method. A SEM or AFM image is taken of the cross-sectional structure of the fibre in question. An accurate representation of the structure, suitable for use in computer modelling, is obtained from the SEM by estimating the position of the structural boundaries throughout the cross-section. Based on this representation, the mode field can be simulated by solving Maxwell's vector wave equation for the fibre structure, using known  
 25 techniques. In brief, Maxwell's equations are recast in wave equation form and solved in a plane wave basis set using a variational scheme. An outline of the method may be found in Chapter 2 of the book "Photonic Crystals – Molding the Flow of Light", J.D. Joannopoulos et al., ©1995 Princeton University Press. This knowledge of the electric and magnetic field distributions enables both the numerator and denominator in Equation (7) above to be  
 30 calculated. The fraction  $\eta$  of light in air may also be calculated by superimposing the modelled mode on the modelled structure.

The values for light power in air  $\eta$  and F-factor are plotted in the graphs in Figures 9a and 9b respectively. In generating the plots of Figures 9a and 9b, the fibre structure of Figure



8 was modelled on a computer and the proportion of light in air  $\eta$  and the F-factor were calculated for various boundary vein thicknesses  $t$ . Each point in the plots represents one thickness, according to the values in Table 1.

The plots demonstrate that  $\eta$  and F-factor vary considerably with core boundary vein  
5 thickness. In particular, the maximum value for  $\eta$  and the minimum value of F-factor appear for boundary vein thicknesses between approximately  $0.318\mu\text{m}$  and  $0.336\mu\text{m}$ . This range is slightly below the maximum anti-resonance value for boundary thickness of  $0.392\mu\text{m}$ , which was calculated above for the tube, but is in-keeping with the proposition that the 'effective' boundary thickness is, in fact, greater due to the silica boundary veins that join the core  
10 boundary.

Following on from this, it will be apparent that different cladding structures, in which different numbers or shapes of boundary vein (or, indeed, other forms of relatively high refractive index material) meet the core boundary, will cause the effective boundary thickness to vary for a given absolute boundary vein thickness. While it might be relatively complex to  
15 model anti-resonance for such boundaries, which may differ significantly from a tube or even a dodecagon, by following the teachings provided herein, the skilled person will be able to calculate  $\eta$  or F-factor and use either one as a proxy to design an anti-resonant boundary.

Figure 10 illustrates one way of arranging a stack of capillaries 1200 to be drawn into a pre-form and fibre of the kind that is exemplified by Figure 8. The cladding is formed by  
20 stacking round cross-section capillaries 1205 in a close-packed, triangular lattice arrangement. The cladding capillaries 1205 have an outer diameter of  $1.04\text{mm}$  and a wall thickness of  $40\mu\text{m}$ . The inner region 1210 of the stack contains a large diameter capillary 1215 having an outer diameter of  $4.46\text{mm}$  and a wall thickness of  $105\mu\text{m}$ . The large diameter capillary 1215 supports the cladding capillaries while the stack is being formed and eventually becomes part  
25 of the material that forms a core defect boundary 145. The resulting structure has a boundary wall thickness in the region of 7% of the pitch, which is below the optimum region for anti-resonance.

Interstitial voids 1220 that form at the locus of each close-packed, triangular group of three cladding capillaries are each packed with a glass rod 1225, which has an outer diameter  
30 of  $0.498\text{mm}$ . The rods 1225 are inserted into the voids 1220 after the capillaries have been stacked. The rods 1225 that are packed in voids 1220 assist in forming cladding nodes 160, which have a diameter that is significantly greater than the thickness of the veins that meet at

the nodes. Omission of a rod from a void in the cladding would lead to the formation of a cladding node that has a significantly smaller diameter.

The stack 1200 is arranged as described with reference to Figure 10 and is then over-clad with a further, relatively thick walled capillary (not shown), which is large enough to contain the stack and, at the same time, small enough to hold the capillaries and rods in place. The entire over-clad stack is then heated and drawn into a pre-form, during which time all the interstitial voids at the boundary, and remaining voids between the glass rods and the cladding capillaries, collapse due to surface tension. The pre-form is, again, over-clad with a final, thick silica cladding and is heated and drawn into optical fibre in a known way. If surface tension alone is insufficient to collapse the interstitial voids, a vacuum may be applied to the interstitial voids of the pre-form, for example according to the process described in WO 00/49436 (The University of Bath).

The thickness of the boundary resulting from the stack in Figure 10 is varied by using different thicknesses of large diameter capillary 1215.

Figure 11 is an SEM image showing a transverse cross section of a seven-cell core defect PBG fibre having boundary thickness of around 7% of the pitch, made according to the preceding method.

Figure 12 is a diagram of an alternative embodiment of the present invention in which a dodecagonal core boundary varies in thickness about the core, with the longer boundary veins being thicker than the shorter ones. The effective thickness of the boundary is a function of the two thickness of boundary vein and their respective lengths as well as the silica that joins to the outer surface of the boundary at boundary nodes.

Figure 13 is a diagram of a further alternative embodiment of the present invention in which a dodecagonal core boundary has alternating short, thin core boundary veins and long, generally elliptical boundary veins, where the minor axis (or thickness) of the ellipses is significantly longer than the thickness of the shorter sides. Hence, the effective thickness of the boundary is a function of the two kinds of boundary vein as well as the silica that joins to the outer surface of the boundary at boundary nodes.

The PBG fibre structures shown in Figures 12 and 13 may be manufactured using known stack and draw methods, wherein preforms are prepared with additional silica rods in regions requiring greater volumes of silica in the final fibre.

The skilled person will appreciate that the various structures described above may be manufactured using the described manufacturing process or a prior art processes. For

example, rather than using a stacking and drawing approach to manufacture, a pre-form may be made using a known extrusion process and then that pre-form may be drawn into an optical fibre in the normal way.

In addition, the skilled person will appreciate that while the examples provided above  
5 relate exclusively to PBG fibre cladding structures comprising triangular arrays, the present invention is in no way limited to such cladding structures. For example, the invention could relate equally to square lattice structures, or structures that are not close-packed. In general, the inventors propose that given a cladding structure that provides a PBG and a core defect in the cladding structure that supports guided modes, the form of the boundary at the interface  
10 between the core defect and the cladding structure will have a significant impact on the characteristics of the waveguide, as described herein.

The skilled person will appreciate that the structures described herein fit on a continuum comprising a huge number of different structures, for example having different combinations of core defect size, boundary vein thickness and, in general, boundary and  
15 cladding form. Clearly, it would be impractical to illustrate each and every variant of PBG waveguide structure herein. As such, the skilled person will accept that the present invention is limited in scope only by the present claims.

CLAIMS

1. An optical waveguide, comprising:

a core, comprising an elongate region of relatively low refractive index;

5 a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light including an operating wavelength of light, the structure, in a transverse cross section of the waveguide, surrounding the core and comprising elongate relatively low refractive index regions interspersed with elongate relatively high refractive index regions; and

10 a relatively high refractive index boundary at the interface between the core defect and the photonic bandgap structure, the boundary having a thickness around the core such that the boundary is an anti-resonant reflector at the operating wavelength of light.

2. An optical waveguide, comprising:

15 a core, comprising an elongate region of relatively low refractive index;

a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light, the structure, in a transverse cross section of the waveguide, surrounding the core and comprising elongate relatively low refractive index regions interspersed with elongate relatively high refractive index regions; and

20 a relatively high refractive index boundary at the interface between the core defect and the photonic bandgap structure, the boundary having a thickness around the core such that, in use, light guided by the waveguide is guided in a transverse mode in which, in the transverse cross-section, more than 95% of the guided light is in the regions of relatively low refractive index in the waveguide.

25

3. A waveguide as claimed in either preceding claim, in which the boundary has a thickness such that, in use, light guided by the waveguide is guided in a transverse mode in which, in the transverse cross-section, more than 1% of the guided light is in the regions of relatively low refractive index in the photonic bandgap structure.

30

4. A waveguide as claimed in any preceding claim, in which the boundary has a thickness such that, in use, light guided by the waveguide is guided in a transverse mode in

which, in the transverse cross-section, more than 50% of the guided light is in the region of relatively low refractive index in the core.

5. A waveguide as claimed in any preceding claim, in which the boundary has a thickness such that, in use, light guided by the waveguide is guided in a transverse mode providing an F-factor of less than 0.7.
6. An optical waveguide, comprising:
  - a core, comprising an elongate region of relatively low refractive index;
  - 10 a photonic bandgap structure arranged to provide a photonic bandgap over a range of wavelengths of light, the structure, in a transverse cross section of the waveguide, surrounding the core and comprising elongate relatively low refractive index regions interspersed with elongate relatively high refractive index regions; and
  - a relatively high refractive index boundary at the interface between the core defect and
  - 15 the photonic bandgap structure, the boundary having a thickness around the core such that, in use, light guided by the waveguide is guided in a transverse mode providing an F-factor of less than 0.7.
7. A waveguide as claimed in any preceding claim, in which the boundary has a
- 20 substantially constant thickness around the core.
8. A waveguide as claimed in any one of claims 1 to 6, in which the boundary has a thickness that varies around the core.
- 25 9. A waveguide as claimed in any preceding claim, in which the thickness equals  $x\lambda$  around at least a proportion  $y$  of the boundary, where  $\lambda$  is a selected operating wavelength,  $x > 0.16$  and  $y > 0.5$ .
10. A waveguide as claimed in any preceding claim, in which the boundary comprises, in
- 30 the transverse cross-section, a plurality of relatively high refractive index boundary veins joined end-to-end around the boundary between boundary nodes, each boundary vein being joined between a leading boundary node and a following boundary node, and each boundary

node being joined between two boundary veins and to a relatively high refractive index region of the photonic bandgap structure.

11. A waveguide as claimed in any preceding claim, in which, in the transverse cross  
5 section, the photonic bandgap structure comprises an array of the relatively low refractive index regions separated from one another by the relatively high refractive index regions.
12. A waveguide as claimed in claim 11, in which the array is substantially periodic.
- 10 13. A waveguide as claimed in claim 11 or claim 12, in which the array is a substantially triangular array.
14. A waveguide as claimed in any of claims 11 to 13, in which the array has a characteristic primitive unit cell and a pitch  $\Lambda$ .
- 15 15. A waveguide as claimed in claim 14, in which the boundary has a thickness  $t$ , wherein,  $t = u\Lambda$  for a proportion of the boundary  $y$ , where  $u > 0.08$  and  $y > 0.5$ .
16. A waveguide as claimed in any preceding claim, in which at least two of the higher  
20 index regions in the photonic bandgap structure are connected to each other.
17. A waveguide as claimed in claim 16, in which the higher regions in the photonic bandgap structure are interconnected
- 25 18. A waveguide as claimed in any preceding claim, in which the photonic bandgap structure comprises an arrangement of isolated relatively low refractive index regions separated by connected regions of relatively high refractive index.
19. A waveguide as claimed in any preceding claim, in which the core has, in the  
30 transverse cross-section, an area that is significantly greater than the area of at least some of the relatively low refractive index regions of the photonic bandgap structure.

20. A waveguide as claimed in claim 19, in which the core has, in the transverse cross-section, an area that is greater than twice the area of at least some of the relatively low refractive index regions of the photonic bandgap structure.

5 21. A waveguide as claimed in any preceding claim, in which the core has, in the transverse cross-section, an area that is greater than the area of each of the relatively low refractive index regions of the photonic bandgap structure.

22. A waveguide as claimed in any preceding claim, in which at least some of the  
10 relatively low refractive index regions are voids filled with air or under vacuum.

23. A waveguide as claimed in any one of claims 1 to 21, in which at least some of the relatively low refractive index regions are voids filled with a liquid or a gas other than air.

15 24. A waveguide as claimed in any preceding claim, in which at least some of the relatively high refractive index regions comprise silica glass.

25. A waveguide as claimed in any preceding claim, in which the relatively low refractive index regions make up more than 75% by volume of the photonic bandgap structure.

20

26. A waveguide as claimed in claim 25, in which the relatively low refractive index regions make around 87.5% by volume of the photonic bandgap structure.

27. An optical fibre comprising a waveguide according to any one of the preceding  
25 claims.

28. An optical fibre transmission system comprising a transmitter, a receiver and an optical fibre, as claimed in claim 27, for transmitting light between the transmitter and the receiver.

30

29. Data conditioned by having been transmitted through a transmission system as claimed in claim 28.

30. A method of forming elongate waveguide, comprising the steps:  
 forming a preform stack by stacking a plurality of elongate elements;  
 omitting, or substantially removing at least one elongate element from an inner region  
 of the stack; and

5 heating and drawing the stack, in one or more steps, into a waveguide of a type  
 described above as being according to the invention.

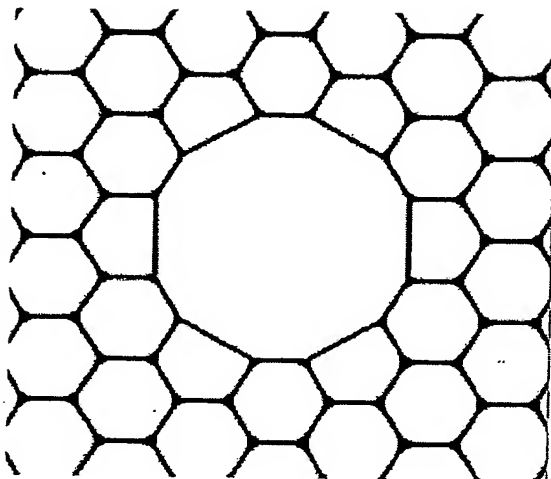
31. A method of forming elongate waveguide for guiding light, comprising the steps:  
 simulating the waveguide in a computer model, the waveguide comprising a core,  
 10 comprising an elongate region of relatively low refractive index and a photonic bandgap  
 structure arranged to provide a photonic bandgap over a range of wavelengths of light, the  
 structure comprising elongate regions of relatively low refractive index interspersed with  
 elongate regions of relatively high refractive index, including a boundary region of relatively  
 high refractive index that surrounds, in a transverse cross-section of the waveguide, the core,  
 15 wherein properties of the boundary region are represented in the computer model by  
 parameters; and  
 finding a set of values of the parameters that, according to the model, increases or  
 maximises how much of the light guided by the waveguide is in the regions of relatively low  
 refractive index in the waveguide.

20

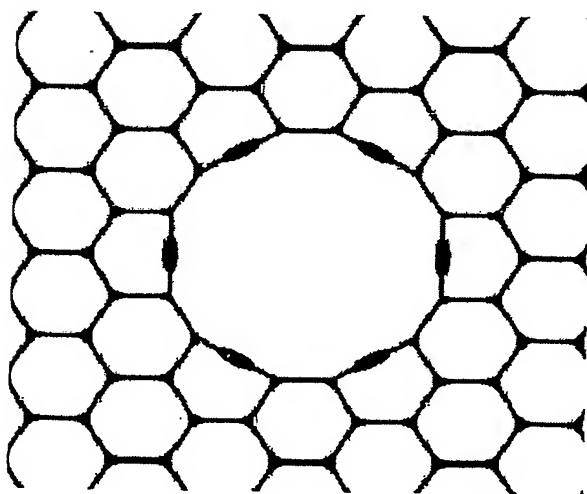
32. A method of forming elongate waveguide for guiding light, comprising the steps:  
 simulating the waveguide in a computer model, the waveguide comprising a core,  
 comprising an elongate region of relatively low refractive index and a photonic bandgap  
 structure arranged to provide a photonic bandgap over a range of frequencies of light, the  
 25 structure comprising elongate regions of relatively low refractive index interspersed with  
 elongate regions of relatively high refractive index, including a boundary region of relatively  
 high refractive index that surrounds, in a transverse cross-section of the waveguide, the core  
 wherein properties of the boundary region are represented in the computer model by  
 parameters; and  
 30 finding a set of values of the parameters that, according to the model, decreases or  
 minimises the F-factor of the waveguide.



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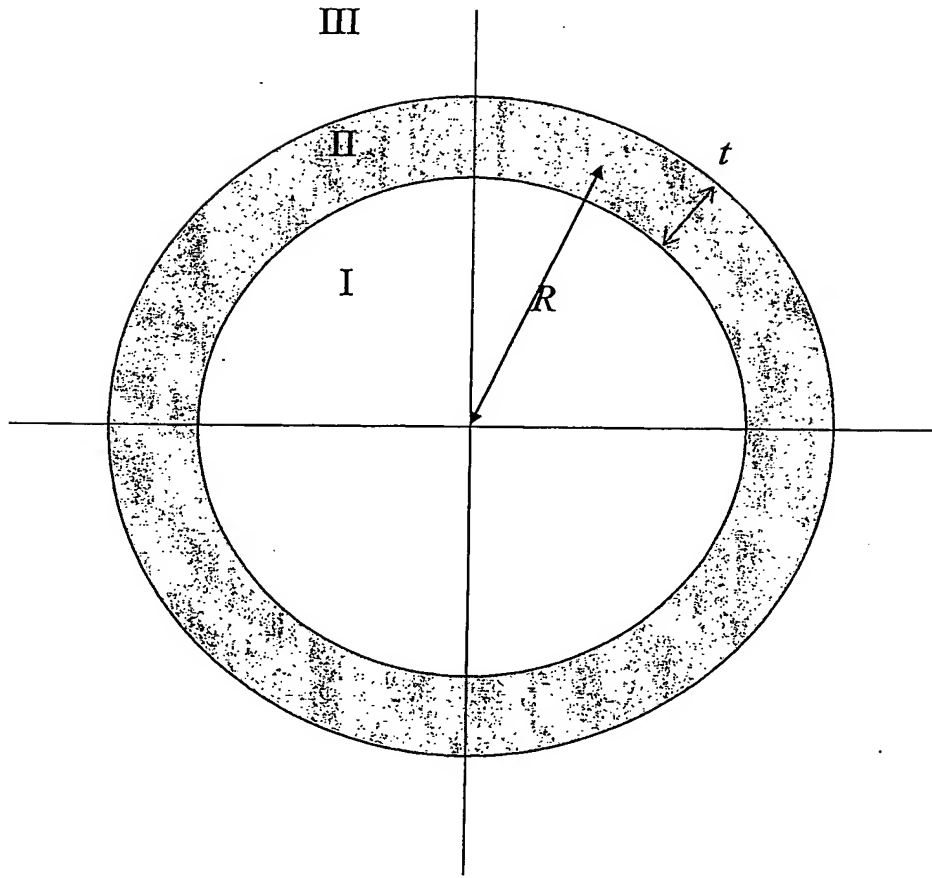


**Figure 1**



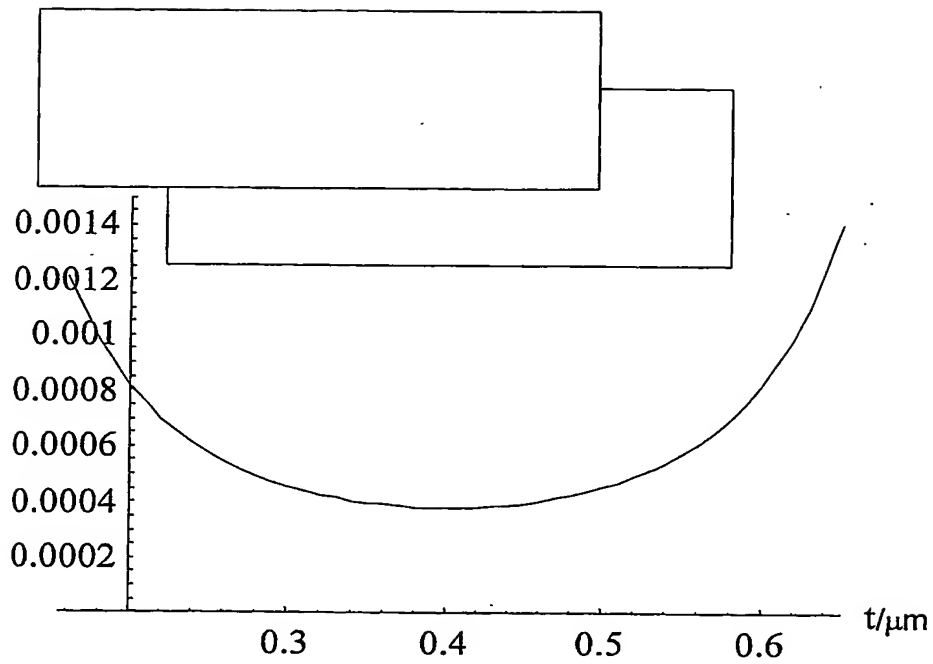
**Figure 2**

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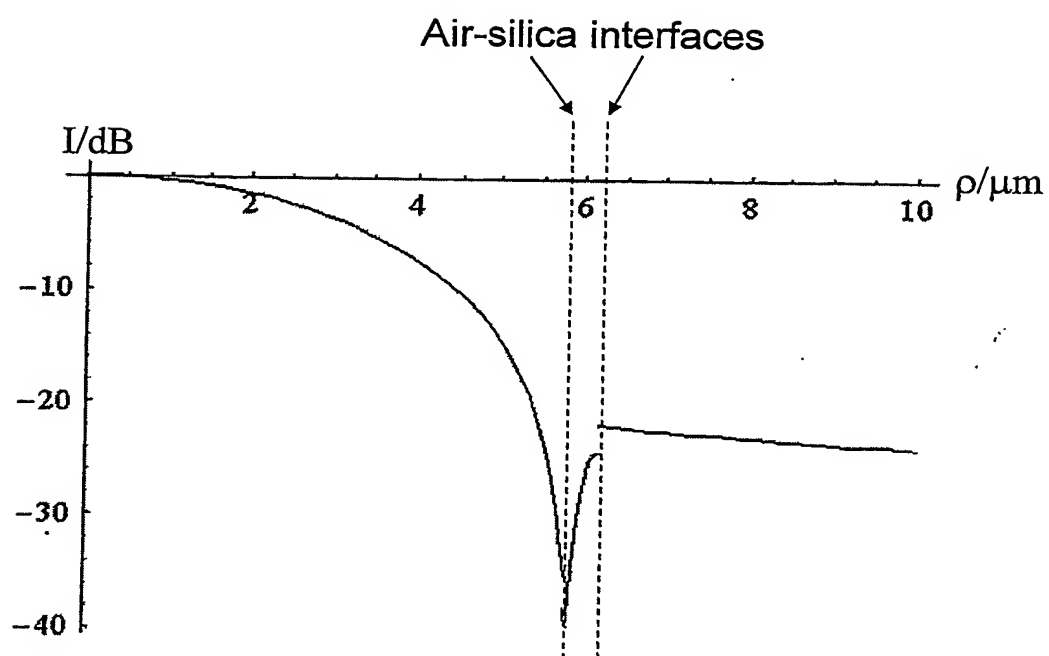
**Figure 3**

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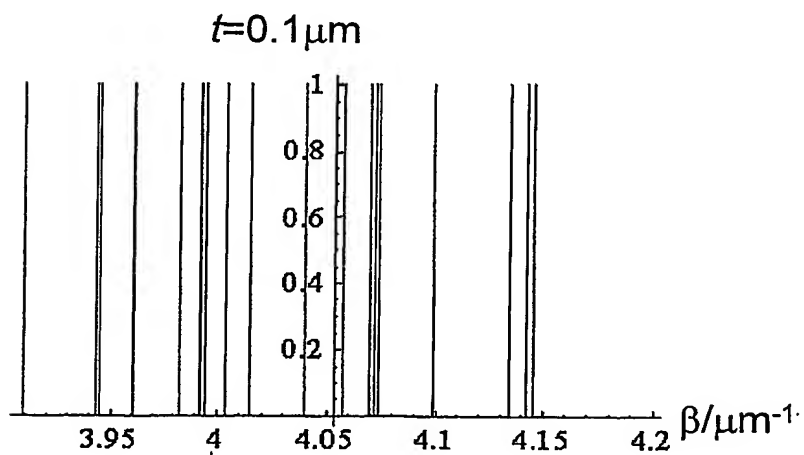
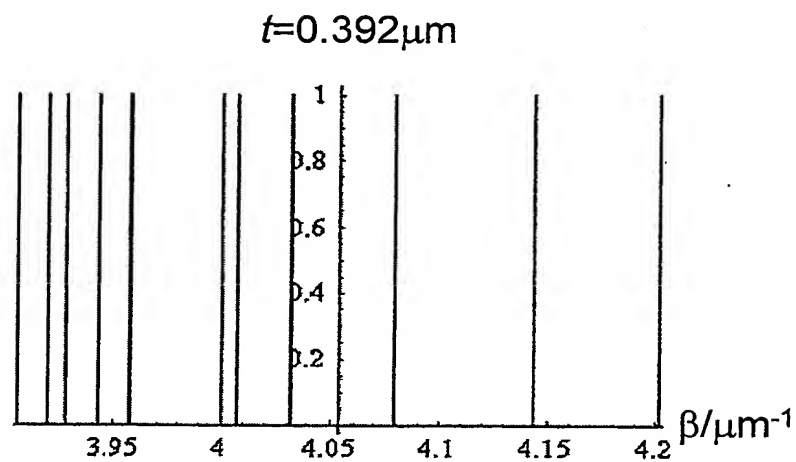
**Figure 4**

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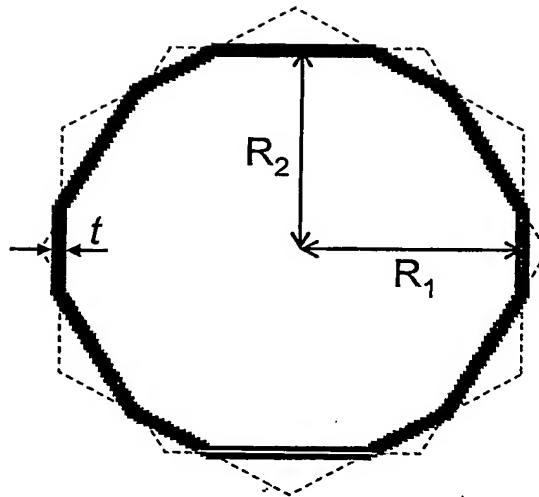
**Figure 5**

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**Figure 6**

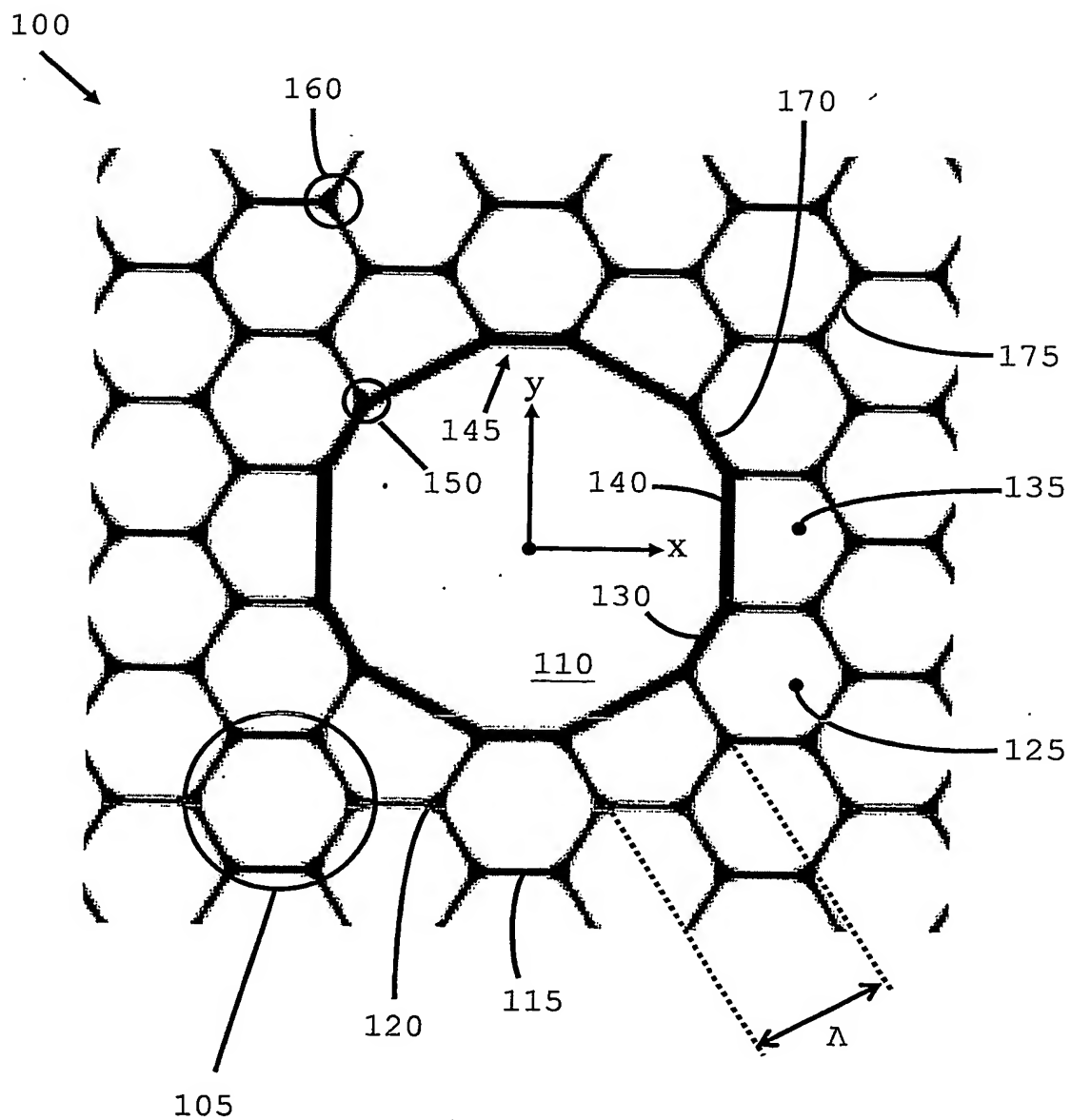
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$$R_1 = \frac{3\sqrt{3}}{5} R_2$$

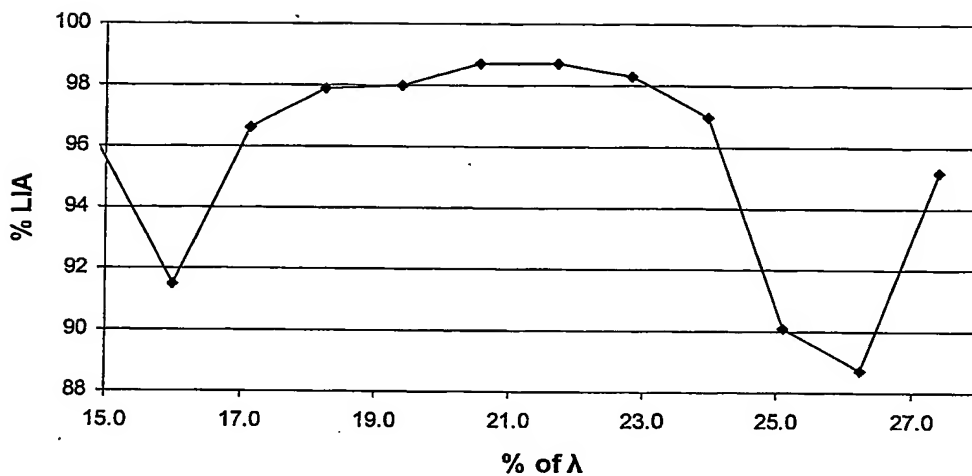
**Figure 7**

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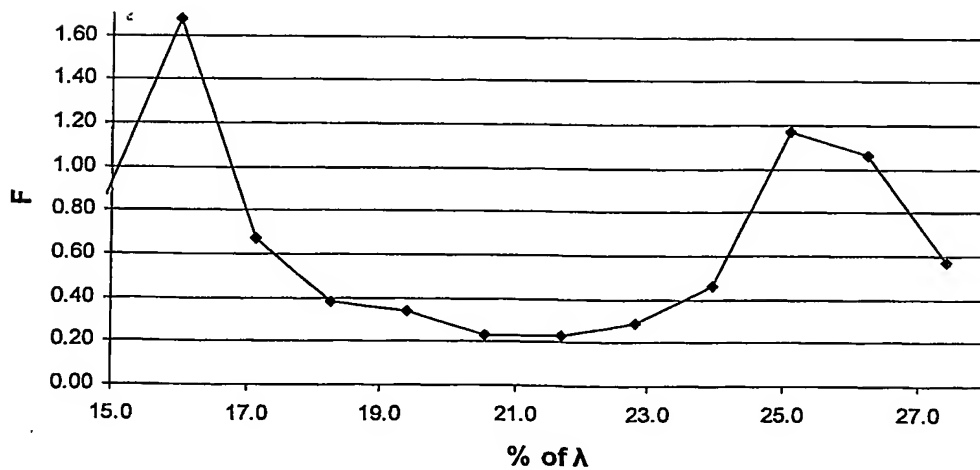


**Figure 8**

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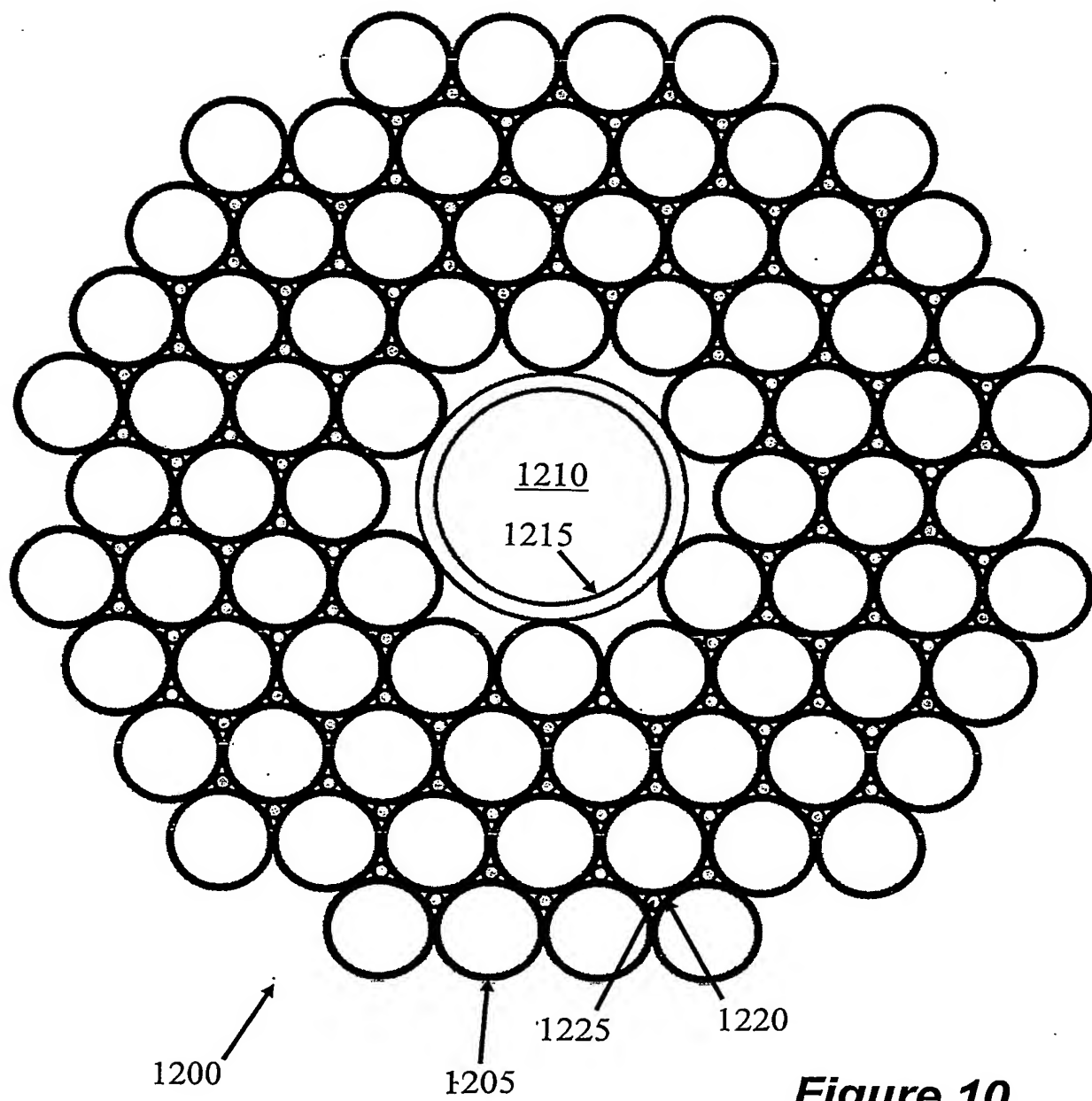
**Figure 9a**



**Figure 9b**

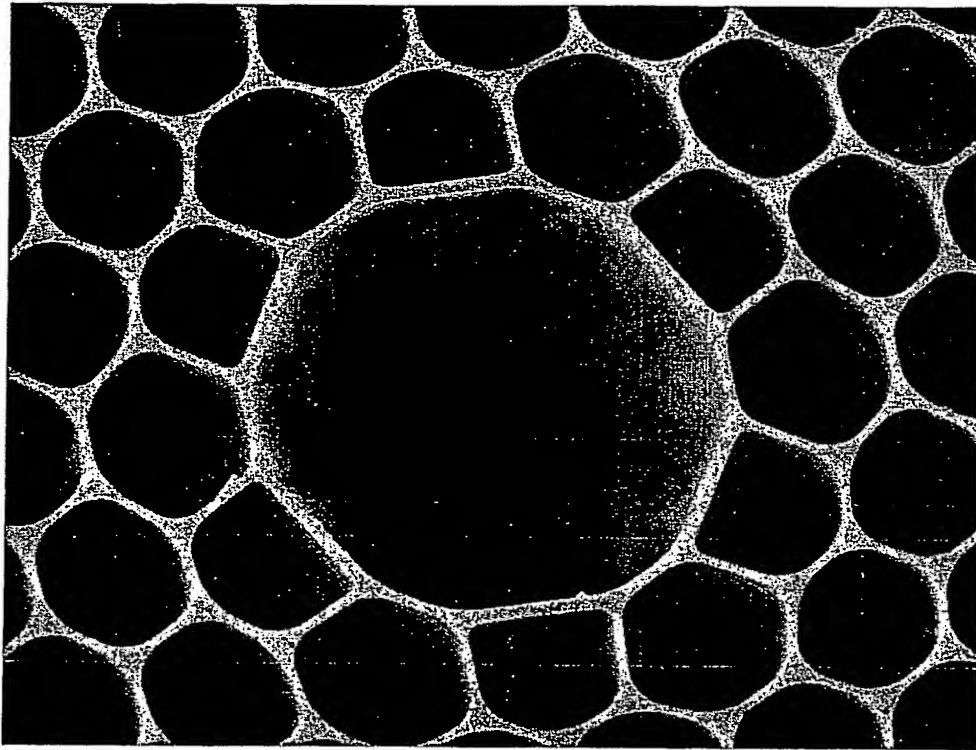


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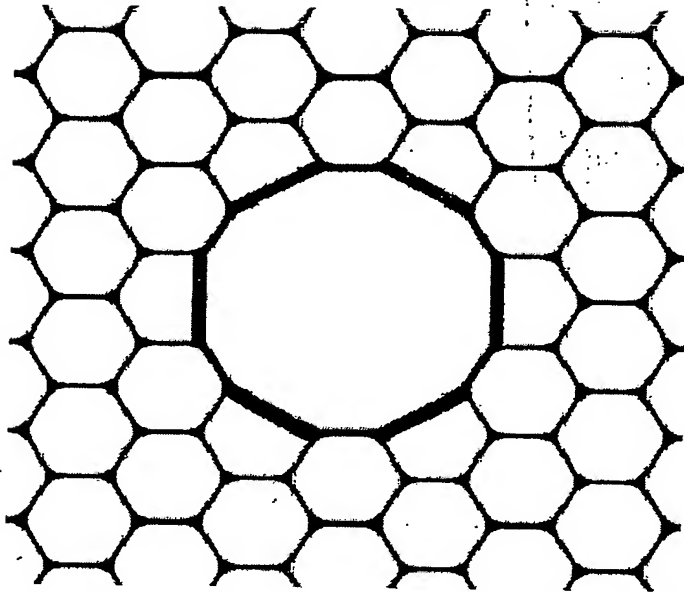
**Figure 10**

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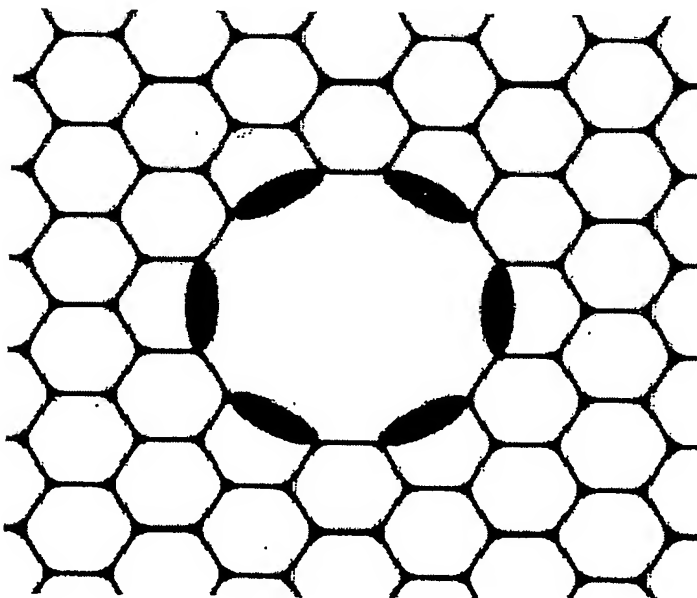


**Figure 11**

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**Figure 12**



**Figure 13**

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